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The decay of As^{76} to Se^{76}

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With 6 figures in the text

ABSTRACT

The gamma rays have been investigated by means of a double focusing spectrometer and a scintillation apparatus. Transitions of the following energies (keV) and relative intensities were found: 559.28 ± 0.10 (100), 657.36 ± 0.15 (14.1), 767.9 ± 2 (0.17), 869.1 ± 2 (0.24), 1216.0 ± 0.4 (9.7), 1228.7 ± 0.5 (2.3), 1438.3 ± 1.0 (1.2), 1453.5 ± 1.4 (0.54), 1788.6 ± 1.2 (0.71), 2097.2 ± 1.0 (1.32), 2111.8 ± 1.2 (0.73), 2433.6 ± 3 (0.05), 2656.1 ± 1.5 (0.077). Coincidence spectra were taken with two NaI(Tl) detectors, and the results were analysed quantitatively. The decay scheme proposed involves levels at 559.3, 1216.6, 1788, 2112, 2434, and 2656 keV. The highest excited state is now known to have the spin of 3, and the *ft*-value as well as the presence of a detectable ground state transition indicate that the parity is odd and that the level should be considered as produced by octupole vibration.

1. Introduction

As^{76} decays by negaton emission with a 26 hours half-life to $_{34}Se^{76}$, exciting several levels of this nucleus. The decay has been investigated by many workers using various techniques. It would not be feasible to review all the findings from earlier works, and since these first-discovered features have been well verified in later works by means of better apparatus, only some recently reported data will be summarized here.

The continuous beta spectrum has been investigated by several authors [1–5] using magnetic spectrometers, the data here being arranged in table form (Table I). The results of these works evidently agree well as to the energy of the extreme end point and all these workers report to have obtained, for the highest branch, a curved Fermi-plot which could be rectified by the application of the appropriate correction factor for once forbidden unique transitions. If this branch is assumed to lead to the ground state, this observation concerning the spectral shape becomes in agreement with a recent determination [6] of the spin of As^{76}, which yielded the result $I = 2$. After subtraction of this highest component the remaining distribution exhibited a maximum energy of 2400 keV about which the agreement is still excellent. Further decomposition into branches of lower energy was made by the use of certain assumptions concerning the level scheme.

The results of the most extensive works [3, 7, 16] concerning the gamma rays have been summarized in Table III together with the data from the present investigation.

Table I. Summary of information on the beta spectrum of As^{76}. Endpoint energies and intensities.

Huber [1]		Tomlinson, Ridgeway [2]		Kurbatov *et al.* [3, 5]		Gregoriev *et al.* [4]	
E_β, MeV	%	E_β, MeV	%	E_β, MeV	%	E_β, MeV	%
2.96^a	53	2.98^a	52	2.965^a	50.5	2.96^a	58
2.40	32	2.40	33	2.41	31	2.41	28
1.75	6	1.76	12	1.76	16	1.76	7
1.20	6			1.20 [5]		0.88	3
0.35	3	0.48	3	0.36	2.5	0.35	4

^{a} $\Delta J = 2$, yes (inferred from shape).

In ref. 3 the gamma energies were obtained by the photo-electron method while the Russian authors used an instrument based on the analysis of Compton electrons (Ritron). The intensity data presented by Kurbatov *et al.* are an average of results from the photospectrum and from scintillation spectra. Utilizing the unusually favourable line-to-background ratio attainable with the "ritron" the Russian group were able to detect nine weak lines which had not been previously reported. It was possible to observe these very weak lines in spite of the rather poor resolution ($\Delta B\varrho / B\varrho > 3\,\%$) by means of a careful analysis of the spectrum. All well defined peaks were fitted to the empirically known window curve of the instrument and the distribution so obtained was subtracted from the experimental spectrum. The result did not come out as zero, but a few statistically significant humps remained, corresponding to counting rates of the order of one count per minute. Gamma rays suggested on such support are indicated in Table III, as in the original presentation, by question marks. Intensities were obtained from a careful calibration by means of isotopes of simple decay.

Kurbatov *et al.* showed by the use of (γ, γ) coincidences that the line of 560 keV is emitted in cascade with each of the lines of 660 keV and 2100 keV. Their further gamma coincidence information was less conclusive but was definitely compatible with their decay scheme, exhibiting levels of 560 keV, 1220 keV and 2610 keV. Beta-gamma coincidences, performed with stilben and sodium iodide crystals, demonstrated the existence of beta branches to states at 560 keV and 1220 keV, which is further support for this level scheme. The first of these states has been studied by Coulomb excitation [8] and quite recently also the second one [9]. The results of Coulomb excitation and of (γ, γ) angular correlation studies [10–13] of the (560, 660) cascade have demonstrated that the spin-parity of the two lowest excited states is 2 +. For the 2610 keV state, Funk and Wiedenbeck [13] have reported a most probable spin of 3, although their data do not exclude the spin value 1.

2. Magnetic spectrometer measurements

The measurements of photon energies and intensities were performed by analysis of photo-electrons with a 50 cm radius double focusing spectrometer. This instrument has been found to be well adapted to photoelectron experiments, since in addition to its excellent focusing properties it has sufficiently large dimensions to permit satisfactory lead shielding between source and detector. In fact, source strengths of a few hundred mC have been used without noticeable increase in counter back-ground. More important still, since the source-to-converter distance is set only by the thickness of copper absorber necessary to stop the beta particles, it is obvious that with a given solid angle from source to converter, one can have higher resolution the larger the instrument.

The magnetic field in the spectrometer is continuously measured relative to that of an iron-free Helmholz coil by means of the synchronous coil method. The field comparison is accurate to better than one part in 10^4.

The original aim of this investigation was a precision measurement of the gamma rays as reported by Kurbatov *et al.* In the course of this work it was discovered that the lines at 1200 keV and 2100 keV were not single lines, and the 1400 keV transition as well was later found to be of double character. A re-investigation of the decay thus naturally suggested itself. The Russian work with Compton secondaries later came to our attention, and it was considered desirable to verify the existence of their additional weak gamma rays by an independent technique.

The As^{76} sources were obtained by neutron irradiation of elementary arsenic, sealed in thin capsules of pure aluminium. All the weak lines have been observed at least once by the use of spectroscopically pure arsenic, obtained from Johnson and Matthey, London, whereas in most cases "pro analysi" samples were used. The irradiations were carried out by AB Atomenergi at a flux of 2–$3 \times 10^{12}/\mathrm{cm}^2$ sec., which resulted in a maximum source strength of about 400 mC. The ampoule was placed inside a copper capsule of a wall thickness calculated to stop all beta radiation. Since the aluminium enclosure was comparable in weight to the arsenic content, it could possibly contribute to the gamma spectrum but an experiment with an irradiated rod of this material showed that such effects were quite negligible.

The only appreciable activity that can be produced by slow neutron irradiation of arsenic is As^{76}, since double neutron capture is negligible. Although for thermal neutrons the reaction $As(n, \alpha)Ga^{72}$ may be estimated to be of negligible probability, this reaction should perhaps be taken into consideration when a fast neutron flux is present, and this also applies to the $(n, 2n)$ and (n, p) reaction. However, no gamma rays have been observed that may be attributed to the decay of isotopes produced in this way.

The precision measurements of energies were carried out with reference to the well known standard lines in the decays of Cs^{137} and Co^{60} and to the annihilation radiation, obtained in this case from Cu^{64}. After demagnetization of the spectrometer the photo-electron lines were measured in order of increasing energy, the calibration sources being introduced at the appropriate regions. The source position was extremely well reproducible since the cylindrical source capsule was clamped to the radiator by means of a phosphor bronze spring provided with a V-shaped indentation. The energies of the lines were generally computed on basis of the position of their high energy edges, taken at half height, since it is our experience that this position is reasonably independent of converter foil thickness. A different procedure had to be used in the experiments involving the annihilation line, since this line shows an appreciable Doppler effect. Here instead the line centre at half height was taken as a measure of the electron momenta, since it was estimated that the relative line shift caused by the converter thickness (1 mg/cm^2) was sufficiently equal for the gamma rays which were compared.

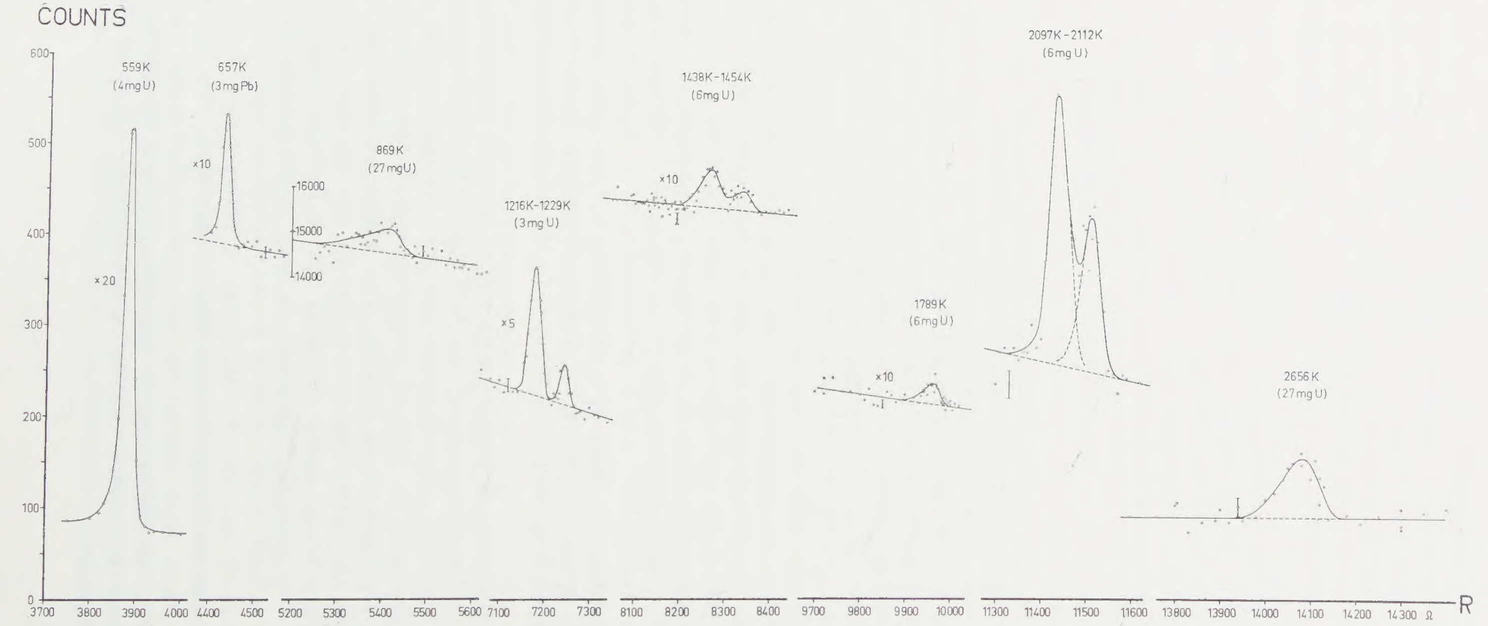

Fig. 1. Diagram showing one sample of each photo-line detected. The symbols within brackets indicate the converter material chosen and the weight of the converter per cm². The relative line halfwidths varied between 0.3 % and 1.0 %, the most usual value being 0.5 %. The potentiometer reading, R, is a linear function of momentum and closely proportional to it.

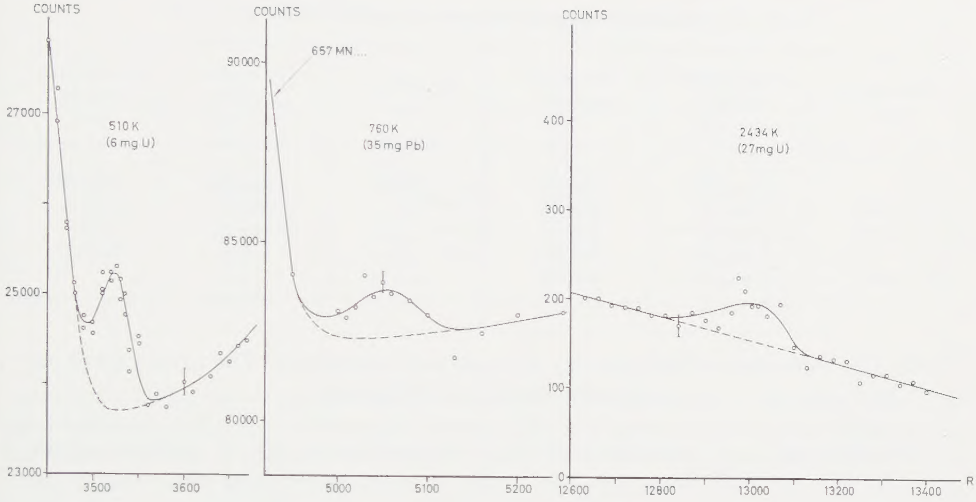

Fig. 2. A few weak gamma rays observed in external conversion.

The photo-electric converters had thicknesses of 1–3 mg/cm^2 in the precise measurements, and sizes of usually 4 × 20 mm^2. For the weakest lines observed, however, a converter as thick as 27 mg/cm^2 had to be chosen. Uranium oxide was generally used as converter material, the foils being prepared by painting with an alcoholic solution of the nitrate and subsequent transformation to the oxide by means of heating. Only in two cases, with the 660 keV and 768 keV gamma rays, was it necessary to use a radiator of lower atomic number, since the uranium *K* lines of these transitions could not be separated from the *L* groups of stronger gamma rays.

Figure 1 shows the photo-electron spectrum. A few additional transitions were found at a later stage after a careful search in certain energy regions, undertaken on indications from scintillation spectra, and these extra lines are shown in Fig. 2. The results of the more precise measurements are given in detail in Table II, and Table III presents the other measurements as well, together with the data of earlier works. The compilation in Table III includes the almost simultaneous work of the Amsterdam group [16].[1] These results were obtained by scintillation techniques. The agreement with the energies given by other workers must be considered as fair, especially in view of the previously unknown complexity of some lines. One of our results is, however, at serious variance with that of Ryde and Andersson [14], who report the value 560.5 ± 0.3 keV from determinations with a curved crystal spectrometer. A deviation in the same sense and of about the same magnitude has also been observed by one of us for the strongest gamma ray in the decay of Au^{194}, this determination being based on an absolute calibration technique. It seems therefore most probable that some systematic error has been present in the experiments of Ryde and Andersson.

It is evident that the lower of the two lines at 1.2 MeV must be identified as the cross-over transition from the second excited state to the ground state. The agreenent of this energy with the sum of the energies of the cascade transitions is perhaps

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[1] We are indebted to these authors for communicating their results before publication.

Table II. Precision measurements of gamma ray energies.

Reference line	Converter weight per cm^2	Transition energy, keV	Reference line	Converter weight per cm^2	Transition energy, keV
Cs^{137}	1 mg Pb	559.28	As^{76} (559)	3 mg Pb	657.40
Cu^{64} (mc^2)	1 mg U	559.33	Co^{60}	3 mg U	1216.1
Cu^{64} (mc^2)	1 mg U	559.22	Co^{60}	3 mg U	1215.7
Cs^{137}	1 mg Pb	657.37	Co^{60}	4 mg U	1216.1
As^{76} (559)	1 mg Pb	657.30			

Table III. Summary of gamma ray energies and intensities. The errors given are estimated standard deviations.

Present work		Dzelepov *et al.* [7]		Kurbatov *et al.* [3]		Girgis *et al.* [16]	
E_γ (keV)	I_γ rel.	E_γ (keV)	I_γ rel.	E_γ (keV)	I_γ rel.	E_γ (keV)	I_γ rel.
510 ±1.5	0.5	—		—		—	
559.28±0.10	100	562	100	549	100	555±5	100
657.36±0.15	14.1	660	14.3	643	20	655±5	14.9
767.9 ±2	0.17	730?	0.5	—		760±20	0.9
869.1 ±2	0.24	870?	0.5	—		860±20	0.9
1216.0 ±0.4	9.7	1222	12.7	1200	21	1210±10	13.0
1228.7 ±0.5	2.3						
—	—	1400?	0.17	—		—	
1438.3 ±1.0	1.2	1430	0.80	1402	2	1430±10	1.05
1453.5 ±1.4	0.54						
—		1510?	0.10	—		1530±20	0.3
—		1620?	0.04	—		1630±20	0.3
1788.6 ±1.2	0.71	1765	0.72	—		1770±15	0.6
—		1850?	0.05	—		1860±20	0.3
2097.2 ±1.0	1.32	2085?	1.95	2053	4	2080±20	1.3
2111.8 ±1.2	0.73					2110±30	0.6
2433.6 ±3	0.05	2500	0.10	—		2410±20	0.13
2656.1 ±1.5	0.077	2740	0.06	—		2640±15	0.12

not fully satisfactory (Table IV). An effect of this kind has been observed several times, and since the low energy transitions have been measured relative to the precisely known annihilation line, it may be that the current value of the Co^{60} gamma ray (1332.6 keV) is somewhat low.

Relationship of the type $E_1 + E_2 = E_3$ between the gamma ray energies as presented in this work have been investigated and a summary is given in Table IV. All the cross-over relationships presented in this table and most of the transitions found may, from the point of view of energies, be accomodated by a decay scheme as proposed by Kurbatov *et al.*, with the addition of levels at 1788 keV, and at 2670 keV. The significance of this evidence will be discussed in the coincidence section.

The gamma ray intensities, as presented in the second column of Table III, were determined by means of the photo-electron method, the analysis of the photo-line

Table IV. Numerical cross-over relationships.

E_1	E_2	E_3	$E_1+E_2-E_3$
559.28	657.36	1216.0	$+0.64 \pm 0.43$
559.28	1228.7	1788.6	-0.6 ± 1.3
559.28	2097.2	2656.1	$+0.4 \pm 1.8$
657.36	1438.3	2097.2	-1.5 ± 1.4
657.36	1453.5	2111.8	-0.9 ± 1.8
869.1	1228.7	2097.2	$+0.6 \pm 2.3$
869.1	1788.6	2656.1	$+1.6 \pm 2.9$
1216.0	1438.3	2656.1	-1.8 ± 1.7

intensities being based on the empirical angular distributions for uranium published by Hultberg *et al.* [15]. In the cases of the 660 keV gamma ray, which could not be measured by the use of a uranium converter, the intensity was inferred from measures of photoline intensities obtained with a lead converter. This determination was carried out relative to the intensity of the 560 keV transition, and the photoelectric efficiency was simply assumed to be proportional to the total photoelectric cross-section. With the double character of some lines taken into consideration, there is generally good agreement between the present intensity data and those of Dzelepov *et al.* [7], which were based on the cross-section for Compton effect. An appreciable difference is, however, met with in the case of the 1430 keV transition.

3. Scintillation single and coincidence measurements

The measurements were made with a conventional scintillation coincidence spectrometer with two differential discriminators and a fast-slow coincidence circuit with an effective resolving time of 3×10^{-8} sec. The fast pulses from the photomultipliers were fed via three halves of E88CC tubes directly to a coincidence tube 6BN6. One NaI(Tl) crystal was $1\frac{1}{2}$ in. in diameter by $1\frac{1}{2}$ in. in height and the other $2\frac{1}{4}$ in. by 2 in. both coupled to RCA 6342 photomultipliers. The distance d between source and crystal was 40 mm. In order to avoid false coincidences due to scattering in the crystals, the detectors were placed at an angle of 90 degrees with a graded Pb-shield between them and 5 mm Al absorbers in front of each crystal to stop the beta rays

Neutron irradiated powder of spectroscopically pure arsenic was used as sources. A single scintillation spectrum of As^{76} in the $2\frac{1}{4}$ in. by 2 in. crystal is shown in Fig. 3 (circles). A number of spectra of standard sources were also taken under identical conditions. The complicated spectrum of As^{76} could then be decomposed into its components by use of the information from the external conversion measurements (Table III) about the gamma energies and the relative intensities of the close doublets. The result of this procedure is also seen in Fig. 3. The curves of fine lines are the component distributions, the dashed lines are partial sums of two or several distributions, and the heavy line curve is the sum of all indicated lines. The weak gamma rays at 510, 768 and 869 keV are not included in Fig. 3. However, the intensity of the 869 keV line is only 0.24 percent of the strong 560 keV line, while the circles indicate the presence of one or more gamma rays of totally about one per cent relative strength. The sum-curve also deviates somewhat from the measured points

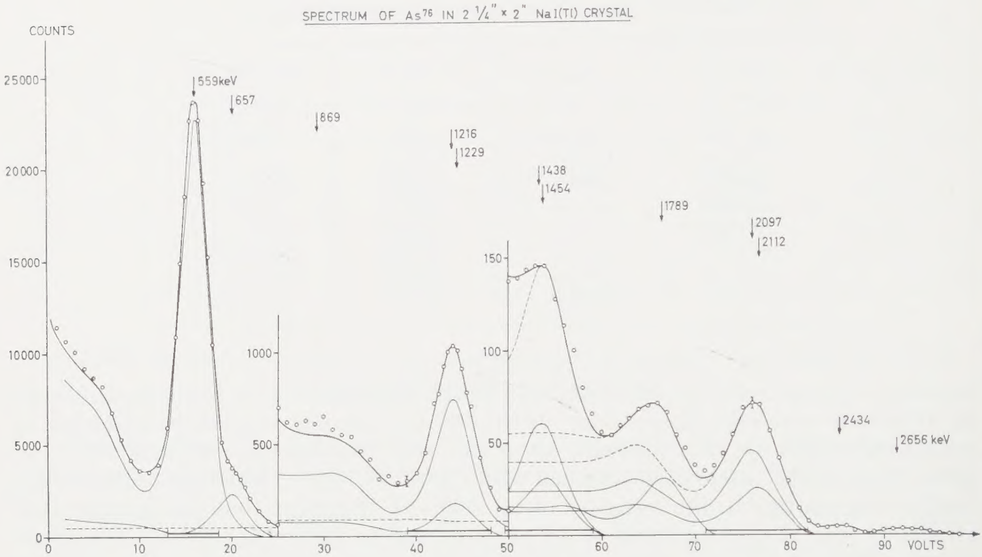


Fig. 3. Single scintillation spectrum of As^{76}. The circles indicate primary data. The curves of fine lines are the component distributions of gamma rays observed in the beta spectrometer measurements. The dashed lines are partial sums of two or more distributions and the heavy line curve is the sum of all indicated lines.

(circles) in the energy regions of about 1550 and 1900 keV. The deviations may indicate weak lines in these energy regions. The areas of the photopeaks of the fine line curves in Fig. 3 yielded relative gamma intensities, after correction for the photopeak efficiency for the $2\frac{1}{4}$ in. by 2 in. crystal. The photopeak efficiency curves for the three crystals used are shown in Fig. 4. The relative gamma intensities from the scintillation spectrum in Fig. 3 agree within ten percent with the values obtained from the photo-conversion measurements (Table III).

Two gamma rays i and j with photopeak counting rates N_i and N_j will produce C_{ij} coincidences

$$C_{ij} = N_i\,\eta_j\,\delta_{ij} = N_j\,\eta_i\,\delta_{ji}, \tag{1}$$

where $\eta_j = \omega_j\,\varepsilon_j$ is the product of the solid angle and the photopeak efficiency for the gamma ray j; δ_{ij} is the fraction of the gamma transition i coincident with the transition j, and δ_{ji} is the fraction of transition j coincident with i. The efficiency of the coincidence unit is here assumed to be unity, and the effect of angular correlation is neglected. Two of the photopeak efficiency curves in Fig. 4 were determined by measuring the relative photopeak areas in the single spectra of Na^{22}, Na^{24}, Co^{60} and Bi^{207} and normalizing these values by coincidence measurements on Na^{24} and Co^{60}, where $\delta_{ij} = \delta_{ji} = 1$. The η-curve for the 3 in. by 3 in. crystal is taken from ref. [19].

Five complete coincidence runs were carried through with the photopeaks of 560, 880, 1220, 1440 and 2100 keV gamma rays selected in the fixed channel with the $2\frac{1}{4}$ in. by 2 in. crystal. The selected parts of the spectra are indicated in Fig. 3, and some of the resulting coincidence spectra are shown in Fig. 5. The source strength

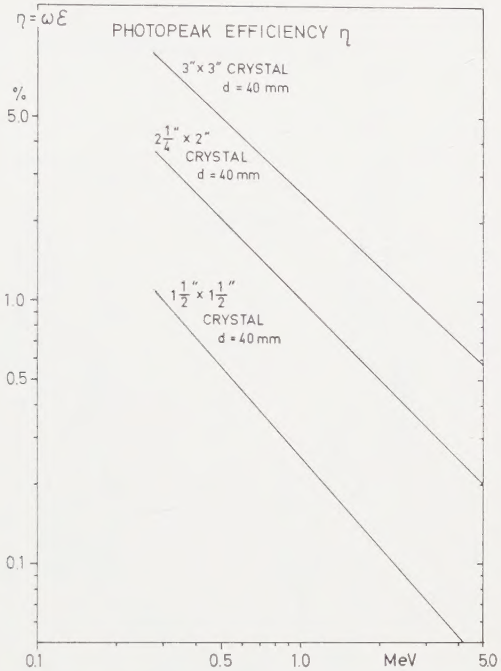
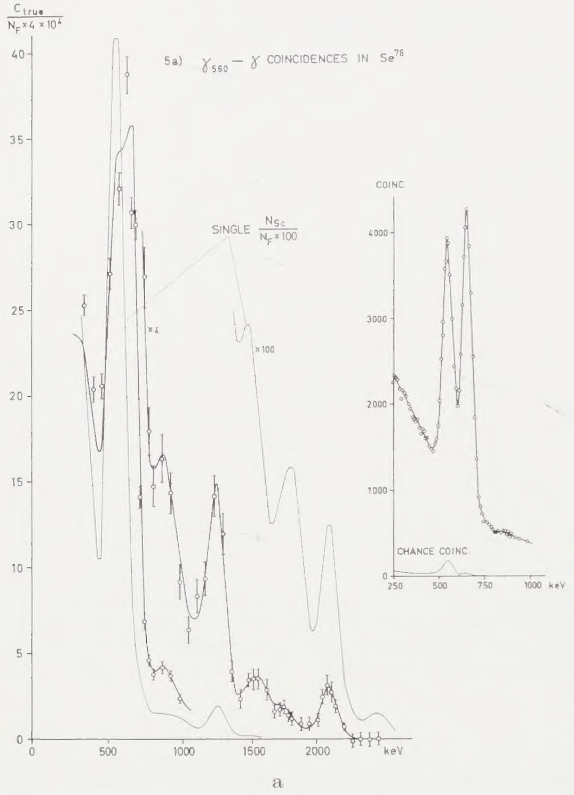


Fig. 4. Photopeak efficiency of the three crystals as a function of energy for a distance $d = 40$ mm between source and crystal. This efficiency includes the solid angle factor.

was always adjusted to give a ratio of true to accidental coincidences larger than eight. The time of measurement on each point was usually 200 to 400 seconds with simultaneously registered coincidence and single counting rates to confirm the channel positions and the stability. These coincidence points in Fig. 5 are corrected for accidental coincidences, and both the single and the coincidence points are normalized against the single counting rate N_F in the fixed channel.

Qualitative coincidence relations can be found from a general comparison of the spectra in Fig. 5. Several gamma rays in the As^{76} decay are, however, of double character and of such an intensity ratio (about one to two) that none can be neglected in a discussion of the coincidence measurements. We thus found it essential to apply a *quantitative* analysis of the coincidence data. The coincidence spectra in Fig. 5 were decomposed into its components. The heavy line curves represent the sums of the component distributions, but the component distributions are excluded in Fig. 5 for the sake of clarity. When a certain energy region around a photopeak from transition $i = 1$ is selected in the fixed channel, the counting rate N_F contains $p_i N_F$ photons from the transitions $i = 1, 2, 3, \ldots (\sum_i p_i = 1.00)$. A photopeak of energy E_j in the coincidence spectrum is thus produced by coincidences between the transition j and the transitions $i = 1, 2, 3, \ldots$ selected in the fixed channel. A coincidence spectrum with j photopeaks thus gives a set of j equations

$$C_j = \sum_i C_{ij} = N_F \eta_j \sum_i p_i \delta_{ij} \qquad (2)$$



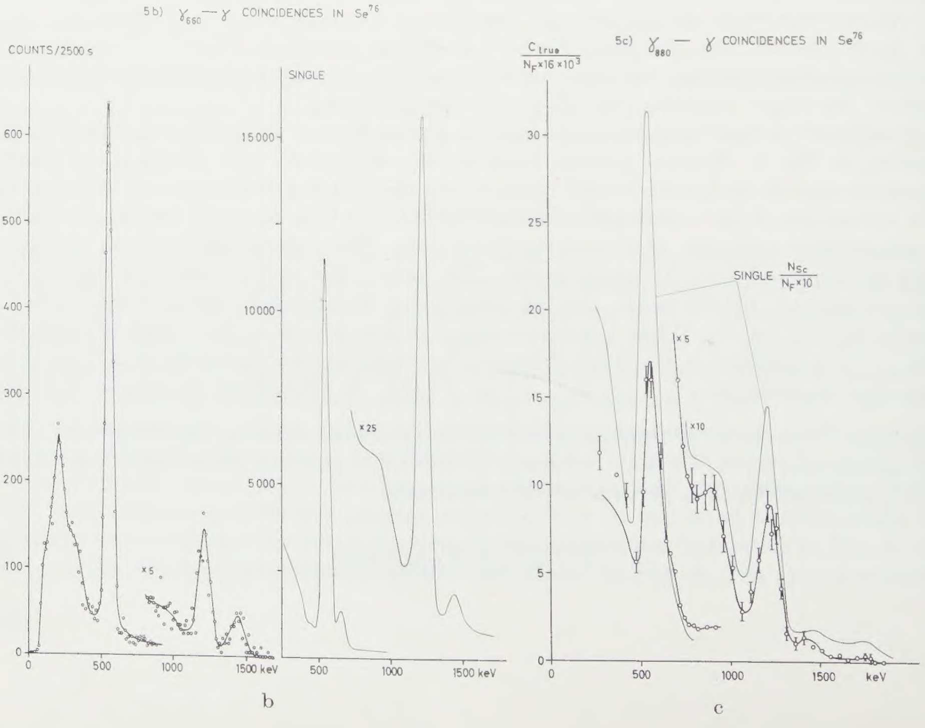
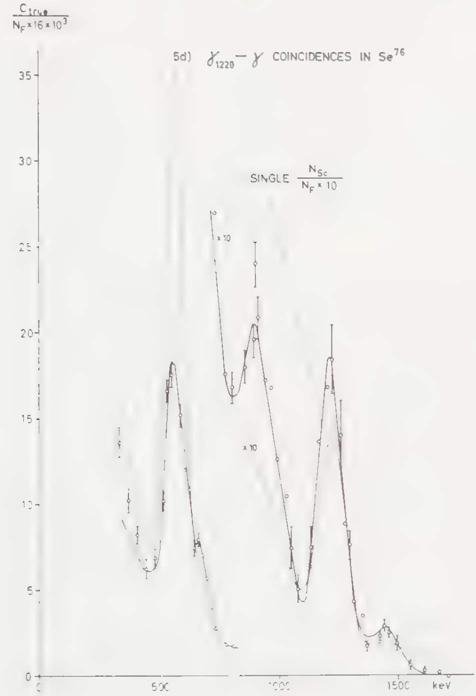
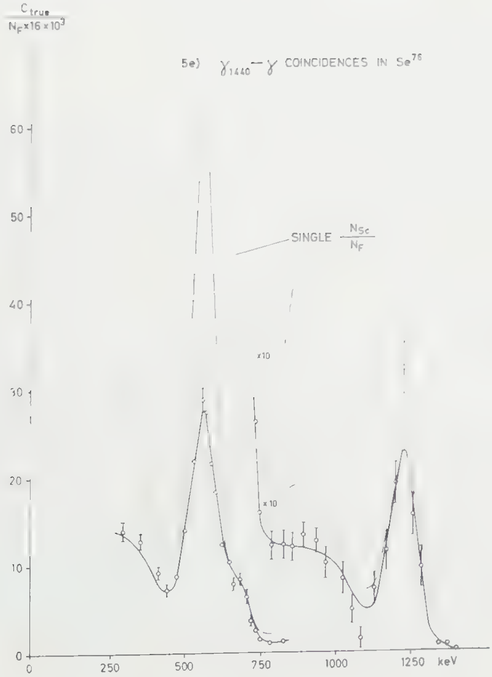


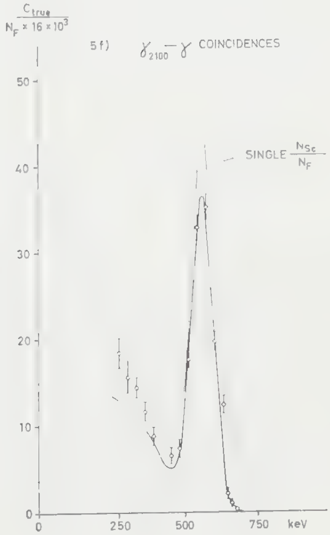
Fig. 5. Coincidence scintillation spectra in a scanning channel (Sc) when the 560, 660, 880, 1220, 1440, and 2100 keV photopeaks respectively are selected in the fixed channel (F). The heavy curves are adjusted to the experimental points, not in an arbitrary manner, but so that they correspond to sum spectra of certain gamma rays.


$\frac{C_{true}}{N_F \times 16 \times 10^3}$
5d) $\gamma_{1220}-\gamma$ COINCIDENCES IN Se^{76}
SINGLE $\frac{N_{Sc}}{N_F \times 10}$
x 10
x 10
0
5
10
15
20
25
30
35
0
500
1000
1500
keV

d


$\frac{C_{true}}{N_F \times 16 \times 10^3}$
5e) $\gamma_{1440}-\gamma$ COINCIDENCES IN Se^{76}
SINGLE $\frac{N_{Sc}}{N_F}$
x 10
x 10
0
10
20
30
40
50
60
0
250
500
750
1000
1250
keV

e


$\frac{C_{true}}{N_F \times 16 \times 10^3}$
5 f) $\gamma_{2100}-\gamma$ COINCIDENCES
SINGLE $\frac{N_{Sc}}{N_F}$
0
10
20
30
40
50
0
250
500
750
keV

f

Table V. Gamma-gamma coincidences.

Coincidence run	Gamma rays selected in fixed channel		Coincident photopeaks (scanning channel)		$100\,\delta_{i,\,j}$ Measured	$100\,\delta_{i,\,j}$ According to the decay scheme Fig. 6
Nr	E_i keV	Fraction of counting rate p_i	E_j keV	Normalized coincidence rate $\frac{C_j}{N_F} \times 10^5$	$100\,\delta_{560,\,j}$	$100\,\delta_{560,\,j}$
1	2	3	4	5	6	7
a	**560**	**0.924**	560	41.6 ± 4.0	3.4 ± 1.0	2.5
	660	0.045	660	55.8 ± 4.3	14.4 ± 3.0	15.1
	1220	0.029	880	2.1 ± 0.6	0.6 ± 0.3	0.5
			1220	6.2 ± 0.4	2.5 ± 1.0	3.5
			1440	0.9 ± 0.3	0.5 ± 0.3	1.3
			1790	0.2 ± 0.2	0.1 ± 0.2	0
			2100	1.6 ± 0.2	1.6 ± 0.5	1.3
			2430	0.00 ± 0.01	0.00 ± 0.03	0
			2650	0.00 ± 0.01	0.00 ± 0.02	0
					$100\,\delta_{660,\,j}$	$100\,\delta_{660,\,j}$
b	560	0.045	560	3200 ± 200	90 ± 20	100
	660	**0.717**	660	15 ± 3	0 ± 2	0
	1220	0.238	880	50 ± 20	1.7 ± 1.2	2.7
			1220	228 ± 30	10.5 ± 2.5	9.2
			1440	85 ± 10	5.2 ± 1.3	5.5
			1790	3 ± 1	0 ± 0.3	0
			2100	1 ± 1	0 ± 0.3	0
					$100\,\delta_{880,\,j}$	$100\,\delta_{880,\,j}$
c	660	0.062	560	200 ± 25	58 ± 20	67
	880	**0.09**	660	47 ± 7	25 ± 15	52
	1220	0.687	880	14 ± 3	10 ± 10	0
	1440	0.061	1220	29 ± 4	45 ± 15	43
	1790	0.029	1440	4.2 ± 1.0	0 ± 10	0
	2100	0.064	1790	0.5 ± 0.2	4 ± 2	4.5
			2100	0.0 ± 0.1	0 ± 2	0
					$100\,\delta_{1220,\,j}$	$100\,\delta_{1220,\,j}$
d	**1220**	**0.837**	560	156 ± 16	28 ± 5	30.0
	1440	0.055	660	47.5 ± 6	11 ± 2	10.8
	1790	0.028	880	11.5 ± 3	4 ± 1	2.7
	2100	0.069	1220	23.5 ± 3	12 ± 3	11.8
			1440	4.0 ± 0.8	3 ± 1	3.5
					$100\,\delta_{1440,\,j}$	$100\,\delta_{1440,\,j}$
e	1220	0.083	560	288 ± 20	79 ± 12	75.7
	1440	**0.451**	660	81 ± 9	42 ± 6	44.6
	1790	0.133	880	0 ± 2	0 ± 3	0
	2100	0.323	1220	25 ± 3	25 ± 5	24.3
	2650	0.011	1440	2.3 ± 1	0 ± 1	0
					$100\,\delta_{2100,\,i}$	$100\,\delta_{2100,\,j}$
f	1790	0.012	560	335 ± 35	70 ± 16	64.4
	2100	**0.956**	660	0 ± 3	0 ± 4	0
	2430	0.01	880	0 ± 2	0 ± 3	0
	2650	0.02	1220	0 ± 2	0 ± 3	0

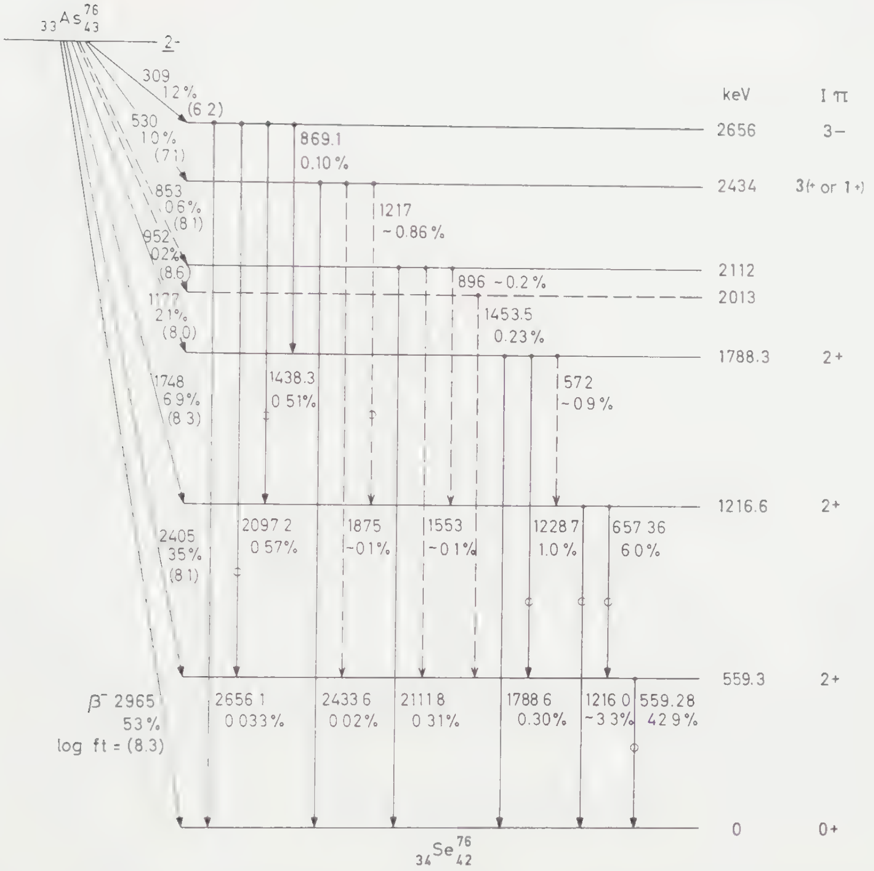


Fig. 6. Decay scheme of As^{76} as obtained from the present investigation. The gamma intensities given are absolute values found by normalizing at 100 % the total intensity to the ground state. Further beta ray intensities and log *ft*-values are then calculated from the gamma intensities. The dashed lines indicate gamma rays from the scintillation and coincidence spectra.

The equations resulting from all the coincidence runs were solved for δ_{ij} by successive approximations, as in most equations all but one p_i value in eq. (2) were $\ll 1$. The results of the analysis of the coincidence measurements are presented in Table V. The η_j values used are taken from Fig. 4 (the $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. crystal). The selected gamma rays, i, and their fractions of the total counting rate N_F in the fixed channel are presented in column 2 and 3 of Table V. As the doublets cannot be separated in the scintillation spectra, their mean energies and sum intensities are given. The next two columns contain the photopeak energies and the normalized counting rates in the coincidence spectra. The δ_{ij} values obtained from the system of equation (2) are given in column 6. It should be noted that δ_{ij} and δ_{ji} are related by the equation $I_i\,\delta_{ij} = I_j\,\delta_{ji}$, where I are the transition intensities. Furthermore, in calculating actual values of δ in the decay scheme, it is useful to remember that for a fixed j-value δ_{ij} takes the same value for all transitions i terminating at a certain level. This redundancy of the δ-values makes it possible to obtain mean values in some cases, and these are used in the construction of the decay scheme, Fig. 6. The δ-values calculated from the decay scheme for comparison are reported in the last column of Table V.

Some of the coincidence measurements were repeated later on in a coincidence spectrometer[1] with a $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. NaI(Tl) crystal (giving 8 % energy resolution for the Cs^{137} photopeak) in the selecting channel and a 3 in. by 3 in. NaI(Tl) crystal in the other channel. The 560 and the 660 keV lines were selected, and the coincident pulses from the big crystal were recorded in a 256 channel apparatus. Parts of these spectra are also presented in Fig. 5. The results obtained from selection of the 560 keV photopeak were very similar to those from the single channel coincidence measurements. The results from the 660 keV coincidence run are included in Table V.

4. The decay scheme

A decay scheme of As^{76} consistent with our measurements is presented in Fig. 6. The relative gamma intensities from Table III are converted to absolute transition intensities by the use of an average intensity of 53 % for the beta transition to the ground state in Se^{76}. (Table I). The error introduced by this normalization is not included in the errors given in the following discussion.

The first two excited states in Se^{76} are observed in Coulomb excitation measurements to be at 560 and 1220 keV [8, 9]. This is in agreement with the data in Table III and V*a*, *b* and Fig. 5*a*, *b* which give a 657.4 keV gamma ray coincident to 100 % with a strong 559.3 keV transition and a cross-over transition of 1216 keV. The level energies are thus 559.3 keV and 1216 keV respectively.

The 2656 and the 2434 keV transitions are not coincident with the 559 keV gamma ray (Table Va) and must thus be ground state transitions. This is consistent with the reported endpoint energy of 2965 keV of the beta transition to the ground state (Table I). Thus two gamma rays, the energy sum of which is larger than 3 MeV, cannot be coincident in the As^{76} decay. The existence of a 2656 keV level is supported by gamma rays feeding the 559 and 1216 keV levels. The energy fit is very good for the 2097.2 and the 1438.3 keV transitions to these levels (Table IV). According to the coincidence data in Fig. 5*a*, *b*, *d*, *e*, *f* and Table V *a*, *b*, *d*, *e*, *f*, 73 ± 14 % of the intensity of the 2100 keV doublet line is coincident with the 560 keV transition, and 65 ± 7 % of the 1440 keV doublet intensity feeds the 1216 keV level; that is, a 2100 keV line of 0.64 ± 0.11 % absolute intensity feeds the 559 keV level and a 1440 keV line of 0.48 ± 0.05 % absolute intensity goes directly to the 1216 keV level.

The energy sum relations in Table IV indicate a level at 1788.3 keV. The coincidence measurements verify the existence of this level, as the 1788 keV transition is not coincident with the 559 keV gamma ray but with a 880 ± 30 keV transition. Table V*a* gives a $\delta_{560,\ 1790} = 0.001 \pm 0.002$, while this value would be 0.007, if the gamma rays were coincident; and Table V*c* shows coincidences between the 1788 and 880 keV gamma rays. If the 1228.7 keV gamma ray is placed between the 1788 and the 559 keV level, 19 % of the 1220 keV intensity will be in direct coincidence with the 559 keV transition, and a mean value of the δ:s in Table V*a*, *b*, *d*, gives 15 ± 10 %.

The strong 559 keV line is found to be coincident with a 560 ± 25 keV transition. The 560 keV peak in Fig. 5*a* may qualitatively be explained by the distributions from all the other gamma rays appearing in the fixed channel accepting the 560 keV photopeak. However, a careful quantitative analysis of the coincidences leaves us with $\delta_{560,\,560} = 0.034 \pm 0.010$, which probably cannot be explained by the coincident bremsstrahlung or by the annihilation radiation observed in the magnetic spectrometer measurements, since the angle between the detectors was 90 degrees, and the energy is outside the limits of error. Although a 560 keV gamma ray directly on top of the 560 keV level is not strictly excluded, the probable solution of the problem is to place a 572 keV gamma ray between the 1788 and 1216 keV levels. The energy of the gamma ray is taken from the level distance and its absolute intensity of about 0.9 % is corrected for the factor of two increase in the efficiency, when two coincident gamma rays of similar energy are selected in both the spectrometers.

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[1] We are thankful to Dr. O. B. Nielsen, Copenhagen, for the loan of this apparatus.

As mentioned earlier, the 2434 keV gamma ray is a ground state transition, defining a level with the same energy. A transition from this state to the 1216.6 keV level would have an energy of 1217.0 ± 3 keV. However, only two gamma rays in the 1220 keV region are observed in the magnetic spectrometer measurements: the cross-over transition of 1216.0 keV from the second excited state and the 1228.7 keV gamma ray to the 559 keV level. The proposed transition would thus have an energy very close to 1216.0 keV or a negligible intensity. The coincidence measurements exclude the possibility of a very small intensity for the 1217 keV transition. 1220–1220 keV coincidences are observed (Fig. 5*d* and Table V*d*), and they still exist after a close inspection of other possible contributions to such coincidences. (See the discussion of the 560–560 keV coincidences.) Fig. 5*b* and Table V*b* also show 1220 keV gamma rays coincident with the 657 keV transition. The combined coincidence data in Table V*a*, *b*, *c*, *d*, *e* give a 1217 keV gamma ray of 0.86 ± 0.10 % absolute transition intensity feeding the 1216 keV level. The cross-over transition from this level then has a relative intensity of 9.7 − 2.0 = 7.7, giving a cross-over to stop-over intensity ratio

$$\frac{I_{1216.0}}{I_{657.4}} = 0.55 \pm 0.04.$$

No coincidences were observed with the weak component of the 2100 keV doublet (27 ± 13 % of the 2100 keV intensity). The 2111.8 keV line is thus a probable ground state transition defining a new level with that energy. The existence of such a state is supported by the coincidences observed with a 900 ± 20 keV line of about 0.25 % absolute intensity directly feeding the 1216 keV level. The energy determination is taken from Fig. 5*d* and the intensity from Table V*b*, *c*, *d*.

The weak component of the 1440 keV doublet does not feed the 1216 keV level but seems to go directly to the 559 keV level. This is concluded from table V*e*, where the $\delta_{1440,\,560}$-value is almost twice that of $\delta_{1440,\,660}$, while they ought to be equal, if both the 1440 keV gamma rays were to feed the 1216 keV level. The two values $\delta_{560,\,1440}$ and $\delta_{1440,\,560}$ yield the result that 22 ± 15 % of the total intensity of the 1440 keV doublet feeds the 560 keV directly. Evidently this indicates that the component at 1453.5 keV (31 %) proceeds from a 2013 keV level to the first excited state. This new level must, however, be considered tentative.

The gamma rays of 1900 keV and 1550 keV resulting from the decomposition of the single spectrum fit into the level scheme from the point of view of energies. The assignments given to the gamma rays on this basis are at least not in conflict with the coincidence results.

5. Conclusion

At the time this work was initiated, the accepted decay scheme was that due to Kurbatov *et al.* The existence of their proposed three excited states, at energies approximately 560 keV, 1217 keV, and 2656 keV, are well confirmed in this investigation. In addition we have found evidence of direct or indirect nature for fourteen new transitions of which twelve have received positions in the decay scheme, although in a few cases somewhat tentatively. New levels could be definitely established at 1788 keV, 2112 keV, and 2434 keV. The decay scheme is in general agreement with that of the almost simultaneous work of Girgis *et al.* [16], where scintillation techniques were used throughout. These workers have developed a very efficient and dependable practice in analysing scintillation spectra, and their gamma ray energies agree extremely well with the more precise data reported here. In the present investigation energies were measured by means of a double focusing spectrometer, and resulting accuracy is of special value in the assignment of cross-over transitions. Also it is believed that the quantitative manner in which coincidences were analysed here is a considerable advantage in a complex decay case.

In the following article Grabowski, Gustafsson and Marklund publish results of angular correlation experiments. They report a spin of 2 for the 1788 keV state, 3 units for the 2656 keV state and alternative values, 3 and 1, for the level at 2434 keV. Considering the log *ft*-value obtained from the gamma intensities (see Fig. 6), there is little doubt that the parity of the 1788 keV level is even, and the opposite assumption would lead to a rather unlikely $M2$ multipolarity for the ground state transition. It is noted that although the energy of the third excited state is almost exactly equal to that calculated from the Davydov–Filippov theory (1776 keV), this theory [18] demands $3+$ character. However, if such a $3+$ state still exists, it would be observable mainly through a transition of energy ≈ 560 keV to the second excited state and with intensity $\approx 1\%$. It is not impossible that a line so close to the strong ground state transition may have escaped notice, and the coincidence measurements do indeed indicate the existence of a transition in that region, coincident with the strong 560 keV line.

The level at 2656 keV has been attributed even parity by earlier workers [7, 13]. The only direct clue as to parity which is given by the data is the log *ft*-value, and it is appreciated that this clue has to be used with caution. However, the conclusion must be that the parity is odd for the reason that the log *ft*-value is clearly lower than that for the first forbidden transitions of the same decay and also lower than that for transitions in other even nuclei. The results of angular correlation reported in following article yield a unique spin of 3 units for the level. If the parity is assumed to be even, there would be an $M3$ transition to the ground state, successfully competing with the $M1$ or $E2$ transitions to the $2+$ states. This would be in violent contradiction to empirical selection rules. If, on the other hand, the level is assumed to be of $3-$ character the ground state transition would be of type $E3$ and the competing transition $E1$. This is the more acceptable alternative, because $E1$ transitions of these energies are known to be strongly hindered. Furthermore, if the level is assumed to be produced by octupole vibration, the transition to the ground state would be enhanced and the cascade transition by way of the $2+$ states would be hindered by the selection rules that apply to collective motion. It seems unavoidable then to assign this state as an octupole vibrational level.

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